CHAPTER 6

PROPAGATION OF RADIOFREQUENCY ENERGY

A radiofrequency current flowing in a wire of finite length produces electromagnetic fields that may be disengaged from the wire and set free in space. If another wire is placed in the path of the electromagnetic field, electrons within the second wire are set in motion. The characteristics of the electron motion with respect to frequency, degree, and direction are similar to those of the original field. If intelligence in some form is being carried by the electromagnetic field, it is reproduced in similar form in the second wire.

RADIOFREQUENCY ENERGY

The whole function of radio communication is to deliver intelligence. In any radio system, r-f energy in the form of electromagnetic waves is generated by a transmitter and fed to a transmitting antenna, the latter radiating this energy out into space. A receiving antenna in the path of the traveling radio wave absorbs part of the energy and sends it through a transmission line to a receiver. The transmission of r-f energy (radio waves) through space is known as wave propagation.

It can be seen that the major components required for transmission of intelligence by means of radio waves are a transmitter, a transmitting antenna (the initial wire), the medium through which the waves travel (the atmosphere), a receiving antenna (the second wire), and the receiving equipment. Successful communications depend chiefly on the power of the transmitter, the distance between the transmitting and receiving antennas, and the sensitivity (ability to amplify weak signals) of the receiver. As will be seen, however, propagation is also affected by such things as the condition of the atmosphere, the type of radio wave transmitted, and the path of the transmission.

GENERAL NATURE AND PROPERTIES

The fundamental nature of electricity has always been a mystery. We know little more about electricity than did the ancient Greeks, who experimented with amber by rubbing it with a cloth to induce forces of attraction and repulsion. Elaborate theories concerning its nature have been postulated, however, and these have gained wide acceptance because of their demonstrated workability. Although electricity never has been defined clearly, rules of behavior exist based mainly on the fact that electricity and electric current always seem to react in a constant and predictable manner.

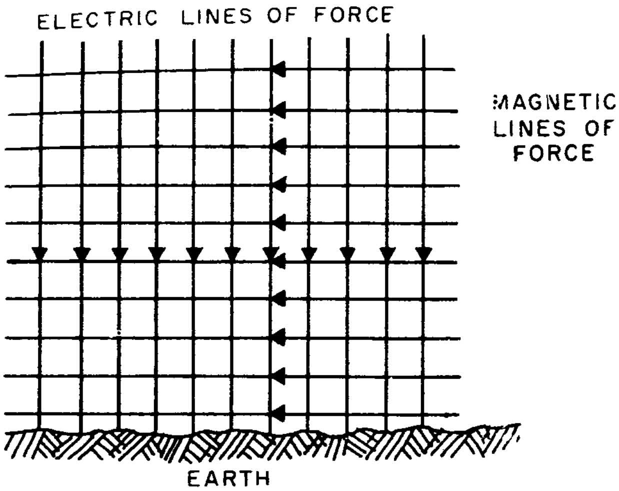
The propagation velocity of r-f energy through free space is approximately 186,000 miles per second—the speed of light. Put another way, it takes 6.1 microseconds (μs) (a microsecond is one-millionth of 1 second) for a wave of radiofrequency energy to travel 1 nautical mile, or 2000 yards. The r-f velocity becomes important when determining antenna length, which is discussed in chapter 7.

A moving electric field always creates a magnetic field, and vice versa. The created field is perpendicular to the parent field, and both are perpendicular to the direction of motion through space. A cross section of the wavefront, then, is composed of moving fields of electric and magnetic lines of force that are at right angles to each other, and both of which are at right angles to the direction of travel, as shown in figure 6-1. (The front can be imagined as moving either toward or away from the reader.)

The general concept of a radio wave is that it radiates outward from the antenna in the same manner that a wave travels across still water into which a rock has been thrown, and that it consists of a series of crests and troughs similar to a water wave. The analogy is not exact, but it serves a useful purpose in that it makes a comparison with a familiar physical action.

POLARIZATION

The lines of force of the electric field are propagated perpendicular to the earth when the transmitting antenna is oriented perpendicular to the earth. In this case the radio wave is said to be polarized vertically. If the transmitting antenna is horizontal, the electric lines of force



20.241
Figure 6-1.—Cross section of a radio wave.

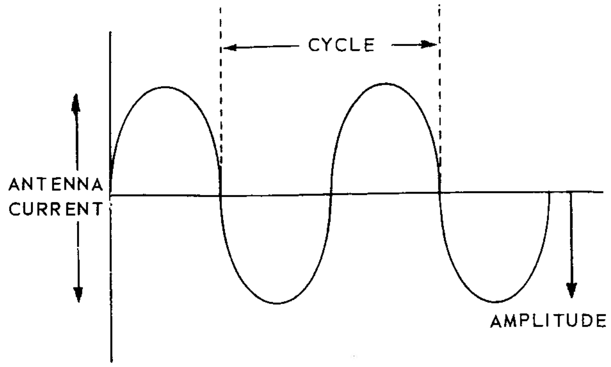
are horizontal and the wave is polarized horizontally. The polarization of the wave may be altered somewhat during travel, but regardless of its position with respect to the earth, the electric and magnetic lines of force always are perpendicular to each other and to the direction of travel.

Polarization of the wavefront is an important consideration in the efficient transmission and reception of radio signals. If a single-wire antenna is used to extract energy from a passing radio wave, maximum pickup results when the antenna is so placed physically that it lies in the same direction as the electric field component. Consequently, a vertical antenna should be used for the efficient reception of vertically polarized waves, and a horizontal antenna should be used for the reception of horizontally polarized waves. In both, it is assumed that the wavefront is traveling parallel to the earth's surface from the transmitting to the receiving antennas. Such a condition does not always prevail, however, as we shall see when we consider the effects of the atmosphere on the behavior of radio waves.

WAVE CHARACTERISTICS

Figure 6-2 illustrates four important aspects of the radio wave: amplitude, wavelength, cycle, and frequency.

The amplitude is the distance from the average level to the peak or trough of the wave, and is the measure of the energy level of the wave. A wavelength is the space (usually measured in



105.4
Figure 6-2.—Characteristics of the radio wave.

meters) occupied by 1 cycle; it may be measured from crest to crest, trough to trough, or from any point to the next corresponding point.

Each cycle is made up of two reversals, the wave moving first in one direction, reversing itself, then returning to the first direction to begin the next cycle. The frequency of a radio wave is the total number of complete cycles the electromagnetic wave goes through in a unit of time; the accepted standard measurement of frequency is in cycles per second (cps). For a radio receiver to obtain useful intelligence, it must be tuned to the same frequency as the transmitter.

FREQUENCY SPECTRUM

Frequencies within the range of 15 to 15,000 cycles per second are called audiofrequencies because vibrations of air particles at any of those frequencies can be heard by the human ear. Above 15,000 cycles per second are the radiofrequencies. Two units are used in speaking of frequencies: kilocycle for 1000 cps, and megacycle for 1,000,000 cps. These are abbreviated kc and mc, respectively. Table 6-1 illustrates the general frequency bands used in communications.

The characteristics of low-frequency propagation differ from those of high-frequency propagation. The choice of a given frequency as the point of division between bands, such as between VHF and UHF, is more or less arbitrary and is agreed upon for convenience.

PROPAGATION OF R-F ENERGY

Characteristics of the atmosphere through which waves of radiofrequency energy pass

Table 6-1. —Designation of Radio Waves According to Frequency

Description	Abbreviation	Frequency
Very low	VLF	Below 30 kc
Low	LF	30 to 300 kc
Medium	MF	300 to 3000 kc
High	HF	3 mc to 30 mc
Very high	VHF	30 mc to 300 mc
Ultrahigh	UHF	300 mc to 3000 mc
Superhigh	SHF	3000 mc to 30,000 mc
Extremely high	EHF	30,000 mc to 300,000 mc

affect the manner of their transmission. Thus, although it sometimes is assumed that radio waves follow perfectly straight paths, properties of the atmosphere are such that the waves are bent and made to follow curved paths.

ATMOSPHERIC PROPAGATION

Propagation of radio waves is affected by reflection, refraction, diffraction, and trapping.

Reflection

Unless the transmitting antenna has a narrow vertical beam that can be elevated, some of the radiated energy must hit the surface of the earth and be reflected. In most instances, energy leaving the antenna follows two paths, one direct to the receiving antenna and the other from the antenna to the surface of the earth and thence to the receiving antenna.

The reflection of a radio wave is like that of any other type of wave, such as light or sound. The amount (efficiency) of reflection depends on the reflecting material. Smooth metal surfaces of good electrical conductivity, such as copper, are efficient reflectors of radio waves. The surface of the earth itself is a fairly good reflector.

Refraction

Refraction occurs whenever there is a change in the medium through which radio waves are passing. The quantity that indicates the degree of bending from a straight-line path is the index of refraction. In homogeneous material, the index of refraction is constant because the waves travel in a straight line; the atmosphere, however, is not a homogeneous medium. Changeable characteristics of the atmosphere are temperature, pressure, and humidity; and these elements vary with altitude. A wave of r-f energy is refracted a small amount in passing from one level of the atmosphere to the next.

In order to establish a reference for the purpose of investigating the effect of atmosphere on propagation, a standard atmosphere has been established. In the standard condition, the temperature, pressure, and moisture content of the air decreases uniformly with height, so that there is a gradual change in the amount of refraction of a wave of r-f energy. Refraction bends the waves downward, thereby increasing the horizontal distance to which the waves can travel. Because of this phenomenon, the distance to the radio horizon is somewhat greater than the distance to the geometric horizon.

Under standard conditions, the change in physical properties of the atmosphere is normally gradual and continuous, the index of refraction changing gradually with increasing height. Consequently, there is no sudden change in the direction of the r-f waves. The standard atmosphere, however, is not necessarily the normal atmosphere at any particular location. Above 10,000 feet the atmosphere almost always is of standard composition, but nonstandard propagation conditions often may exist at a lower altitude.

When nonstandard atmospheric conditions exist, we encounter "anomalous propagation." Under these conditions, the amount of change of temperature, pressure, and moisture varies with altitude at a different rate than normal. As a result, the radio waves undergo greater or less bending than normal, causing the radio horizon to be extended or shortened, depending on the existing conditions.

The temperature may, for example, first increase with height and then begin to decrease. Such a situation is called a temperature inversion. More important, the moisture content may decrease markedly with height just above the sea.

This latter effect, called a moisture lapse, may produce, either alone or in combination with a temperature inversion, a great change in the index of refraction of the lowest few hundred feet of the atmosphere.

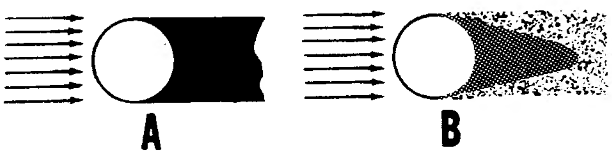
Altered characteristics of the atmosphere may result in an excessive bending of radio waves passing through the lower atmosphere. In certain regions, notably in warm climates, excessive bending is observed as high as 5000 feet. The amount of bending in regions above this height usually is that of normal atmosphere.

A knowledge of refraction characteristics is important to the communicator because radio waves, particularly in the VHF and UHF bands, may be refracted and thus detected hundreds of miles beyond the visible horizon. This point must be borne in mind when a ship is in waters where radio security is essential.

Diffraction

Another consideration from the standpoint of communication security is diffraction, the natural bending of radio waves over the geometric horizon.

The bending effect caused by diffraction can be observed in shadows cast by sunlight. Light rays from the sun are essentially parallel, yet the shadow of a ball does not have sharp, clear edges, as in part A of figure 6-3, because of diffraction. When the waves pass close to the surface of the ball, they are bent inward slightly and penetrate the shadow, partially illuminating its edges as in part B of figure 6-3. The wavelengths of r-f energy are much longer than those of visible light, and the amount of bending caused by diffraction also is greater.



59.21

Figure 6-3. —Bending effect caused by diffraction.

Although r-f energy diffracted around the curve of the earth usually is weak, it may be detected by a suitable receiver. Because low-frequency radio waves are bent more than high-frequency waves, a low-frequency transmission can be intercepted by the enemy at a greater distance than can a microwave transmission, provided the two sets transmit comparable power. The principal effect of diffraction, then, is to extend beyond the radio range of your ship the range of possible interception by enemy surface ships and aircraft of your r-f transmissions.

Figure 6-3 helps explain why radio waves of the proper frequency can be received on the far side of a hill. In the propagation of radio waves at a distance, diffraction is an important consideration because the largest object to be contended with is the curvature of the earth itself.

Trapping

Normally the warmest air is near the earth's surface, but when a temperature inversion occurs, the index of refraction is different for the air within the inversion than for the air outside the inversion. These differences cause the formation of a channel or duct that acts as a waveguide within which transmitted signals are trapped. The result is that the signals are piped many miles beyond the assumed normal range, as shown in figure 6-4.

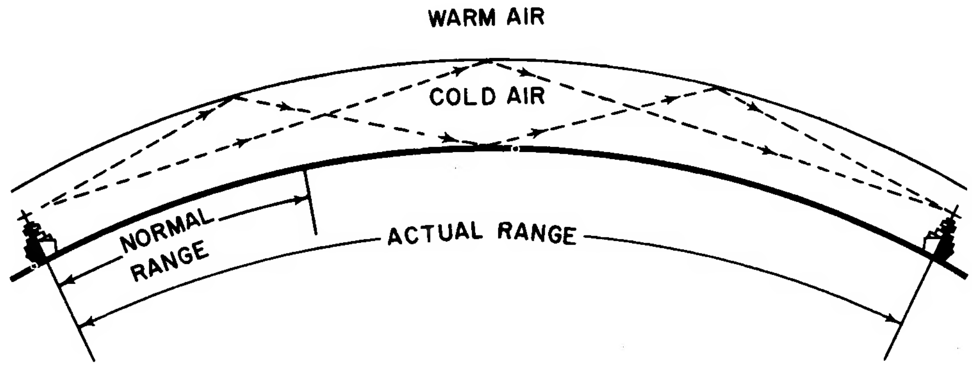
At times these ducts are in contact with the water and may extend a few hundred feet into the air. At other times the duct starts at an elevation of 500 feet or more and extends an additional 500 to 1000 feet upwards.

A necessary feature of duct transmission is that both the transmitting and receiving antennas must be inside the duct. A transmitting antenna above a surface duct will not operate into the duct. Hence, a receiving antenna below a duct receives no signals from an aircraft flying in or above a duct, even though line-of-sight conditions prevail.

The peculiar structure of the atmosphere that produces trapping occurs fairly often in many parts of the world. Several types of meteorological conditions can produce the temperature and humidity gradients necessary for trapping to take place.

SURFACE DUCT. —Warm continental air blowing over a cooler sea leads to formation of a duct by causing a temperature inversion as well as by evaporation of water from the cooler sea into the lower levels of the warm, dry air. The base of such a duct is usually the sea surface with the trapping region extending several hundred feet upward.

Over the open ocean, a surface duct may be formed by cool air blowing over a warmer sea. No temperature inversion is associated with this



20. 255

Figure 6-4. —The duct acts as a signal waveguide.

phenomenon, and the entire effect is caused, apparently, by evaporation of water into the lower levels of the atmosphere. Ducts of this sort are often created by trade winds that have blown for a long distance over the open sea.

ELEVATED DUCT. —An elevated duct may form in an area of high barometric pressure because of the sinking and lateral spreading of the air, termed subsidence. When the air is warm and dry and subsidence takes place over the sea, water is evaporated into the air, forming a moisture gradient that leads to formation of a duct. Such ducts always are formed above the sea, with the base of the trapping layer ranging in elevation from a few thousand to 20,000 feet. Subsidence trapping nearly always can be found in the tropics.

Other meteorological conditions that may produce trapping are cooling of land at night by radiation and mixing two masses of air, as at a warm or cold front. Ducts formed by these effects are likely to be of such limited extent that they are unable to modify propagation by any appreciable amount.

Prediction of Nonstandard Propagation

Sometimes it is possible to predict formation of ducts from observation of weather conditions, coupled with simple measurements that can be made on board any ship.

For a number of reasons, meteorological conditions in a region of high barometric pressure are favorable for forming ducts. Among favorable factors are (1) subsidence, which creates temperature inversions, and which occurs in areas where the air is very dry so that evaporation can take place from the surface of the sea; (2) calm conditions that prevent mixing the lower layers of the atmosphere by turbulence, allowing thermal stratification to persist; and (3) clear skies, which permit nocturnal cooling over land.

Conditions in a barometric low, on the other hand, generally favor standard propagation. A lifting of the air, the opposite of subsidence, usually occurs in such regions and is accompanied by strong winds. The combined effect is to destroy any local stratification of the atmosphere by a thorough mixing of the air. Moreover, the sky usually is overcast in a low-pressure area, and nocturnal cooling is therefore negligible. Rains fall very often in a low-pressure area, and falling drops of water have the effect of destroying any nonstandard humidity or temperature gradients that may have been established.

In all weather conditions that produce trapping, the atmosphere must be sufficiently stable to allow the necessary stratification of the atmosphere to be established and to persist. Thus, continued calm or moderate breezes are necessary. It must be emphasized, however, that even if weather conditions favor formation of ducts, they do not always produce them.

The following weather conditions, which are readily obserable, may favor trapping:

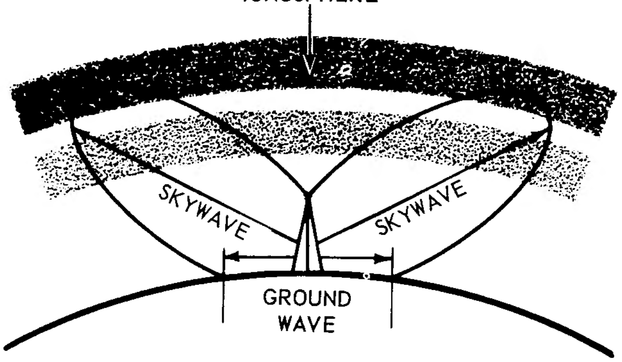
1. A moderate breeze that is warmer than the water, blowing from a continental land mass.
2. Clear skies, little wind, and high barometric pressure.
3. A cold breeze blowing over the open ocean far from large land masses, especially in the tropical trade wind belt.
4. Smoke, haze, or dust that fails to rise but spreads out horizontally, which indicates

quiet air, in which a temperature inversion may exist.

5. When the air temperature at bridge level on a ship definitely exceeds that of the sea, or when the moisture content of the air at bridge level is considerably less than that just above the water, and the air is relatively calm.

RADIO WAVE FORMATION

When a radio wave leaves an antenna, part of the wave moves outward in contact with the ground, the remainder of the wave moving upward to form a skywave, as in figure 6-5. The ground and sky portions of the wave are responsible for two different methods of carrying messages from transmitters to receivers.



13.27

Figure 6-5. —Formation of the groundwaves and skywaves.

Groundwave

The groundwave normally is used for short-range (line-of-sight) communications, although it may be utilized for long-range communications in the low-frequency bands using high power.

A groundwave is composed of two parts, a surface wave and a space wave. The surface wave travels along the ground, while the space wave follows two paths—one through the air from transmitter to receiver, the other reflected from the ground to the receiver. Because the space wave follows two paths of different lengths, the two components may arrive in or out of phase. As the distance from the transmitter changes, the two components may add or cancel.

As it passes over the ground, the surface wave induces a voltage in the earth, setting up eddy currents. The energy to create these currents is taken away from the surface wave, which is weakened as it moves away from the antenna. Increasing the frequency results in a rapidly increasing rate of attenuation. Because of this increased attenuation with increased frequency, surface-wave communication generally is limited to the lower frequencies. The surface-wave component is not confined to the earth's surface, but extends to considerable heights, diminishing in field strength with increased height.

Shore establishments are able to furnish long-range surface-wave communication by using frequencies between 18 and 300 kc with extremely high power.

The electrical properties of the earth over which the surface wave travels are relatively constant, hence the signal strength from a given station at a given point is nearly constant. This holds true in practically all localities, except those that have distinct rainy and dry seasons. In those regions, the difference in the amount of moisture causes the soil's conductivity to change

The best type of surface for surface-wave transmission is sea water. Next in order of desirability are large bodies of fresh water, wet soil, flat loamy soil, dry rocky terrain, desert, and jungle. Because of the superiority of surface-wave conductivity by salt water, high-power, low-frequency transmitters are located as close to the edge of the ocean as practicable.

Not all groundwave communication employs the lower part of the frequency spectrum. For example, VHF-UHF communications use so-called line-of-sight transmission. At these frequencies the direct wave component of the groundwave is increasingly important. It should be noted that whereas the range of the groundwave at low frequencies can be increased effectively only by increasing radiation power, the range of frequencies of 30 mc or higher can be increased effectively by increasing antenna height as well as by increasing radiation power.

Skywave

In high-frequency communications, the skywave is used for long ranges.

The behavior of the skywave is quite different from that of the groundwave. Some of the energy radiated is refracted by an ionized layer of atmosphere, called the ionosphere, and is bounced or relayed back toward the earth. If a receiver is located in the area where the

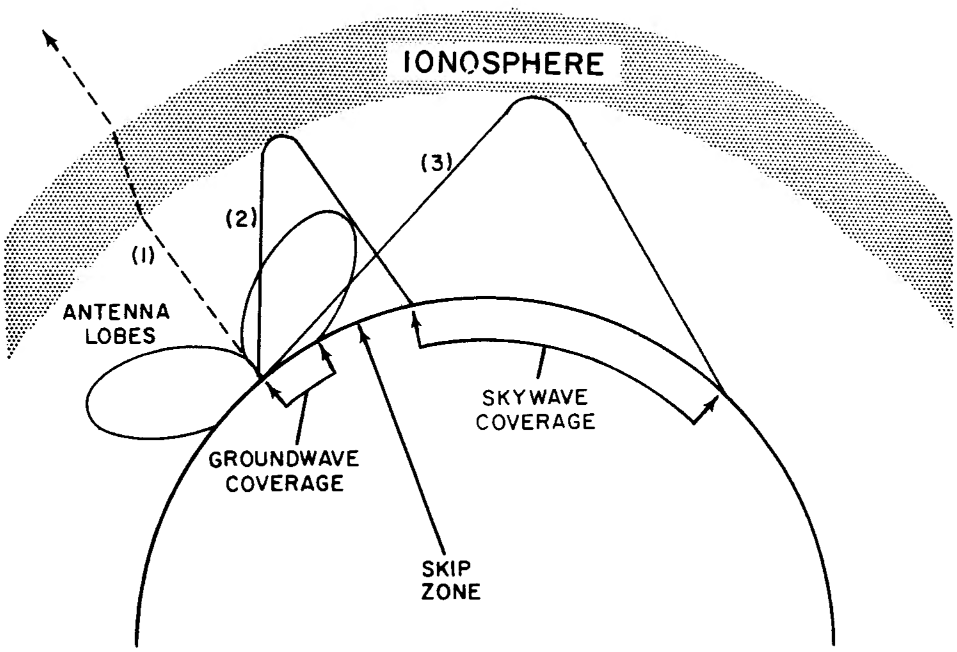
returning wave strikes, it is possible to detect the signals clearly even though the receiver is located several hundred miles beyond the range of the groundwave. The ability of the ionosphere to return a radio wave to earth depends upon the angle at which the skywave strikes the ionosphere, the frequency of the transmission, and upon the ion density.

In figure 6-6 the skywave is assumed to be composed of three rays. The angle at which ray 1 strikes the ionosphere is too nearly vertical for the ray to be returned to earth. The ray is bent out of line, but it passes through the ionosphere and is lost. The angle made by ray 2 is called the critical angle for the frequency. Any ray that leaves the antenna at an angle greater than the critical angle will penetrate the ionosphere. Ray 3 strikes the ionosphere at the smallest angle that will be refracted and still return to earth. At any smaller angle, the ray will be refracted toward earth but will miss it completely. The antenna lobes in figure 6-6 show the generally accepted concept of a beam, or wave, of radiated electromagnetic energy.

As the frequency decreases, the critical angle increases. Low-frequency fields can be projected straight upward and will be returned to earth. The highest frequency that can be sent directly upward and still be returned to the earth is the critical frequency. At sufficiently high frequencies, the wave will not be returned to the earth, regardless of the angle at which the ray strikes the ionosphere.

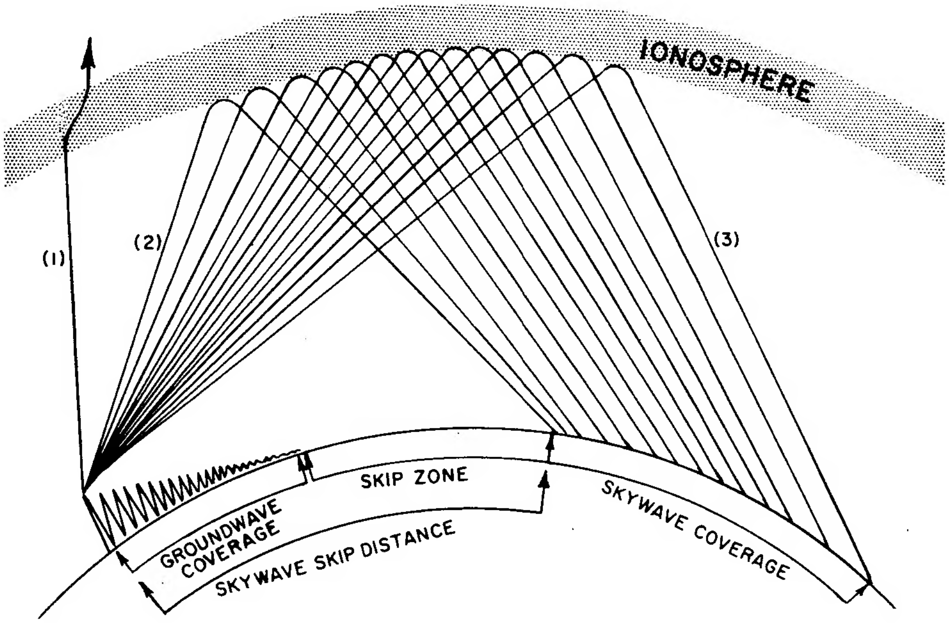
In figure 6-7, note the relationship between skip zone, skip distance, and the groundwave. The skip zone depends on the range of the groundwave; it disappears entirely if the range of the groundwave equals or exceeds the skip distance. The skip distance, which depends on the frequency and the degree of ionization present, is the distance from the transmitter to the nearest point at which refracted waves return to earth. If the skywave returns to earth at a point where the groundwave and skywave are of nearly equal intensity, the skywave alternately reinforces and cancels the groundwave, causing severe fading of the signal. This is caused by the phase difference between the two waves resulting from the longer path traveled by the skywave.

Frequently a skywave has sufficient energy to be refracted and reflected more than one time. It then is known as a double-hop or multiple-hop transmission, and results in the valuable "skip" needed for long-range communications.



13.30

Figure 6-6. —Comparison of skywave transmission paths.



31.17

Figure 6-7. —Relationship between skip zone, skip distance, and groundwave.

IONOSPHERIC PROPAGATION

The study of wave propagation is concerned chiefly with the properties and effects of the actual medium through which radio waves must travel between a transmitting antenna and a receiving antenna. The atmosphere about the earth is not uniform, changing with a change in height or geographical location, or even with a change of time (day, night, season, year). This lack of uniformity influences the passage of radio waves through it, thereby adding many new factors to complicate what at first might seem to be a relatively simple problem. A knowledge of the composition of the earth's atmosphere is extremely important in solving this problem, and therefore, for purposes of understanding wave propagation, various layers of the atmosphere have been distinguished. These are the troposphere, the stratosphere, and the ionosphere.

The troposphere is the portion of the earth's atmosphere extending from the surface of the earth to heights of about 6 1/2 miles. The temperature in this region varies appreciably with altitude. A tropospheric wave is that portion of the groundwave that is refracted in the lower atmosphere by changes in humidity, pressure, and temperature.

The stratosphere lies between the troposphere and the ionosphere. It extends from about 6 1/2 miles to approximately 30 miles above the surface of the earth. The temperature in this region is considered to be almost constant. The stratosphere, because of its constancy, has relatively little effect on radio waves.

The ionosphere is that portion of the earth's atmosphere above the lowest level at which ionization affects the transmission of radio waves. The ionization of this layer is large compared with that near the surface of the earth. For the purpose of study, the ionosphere extends from about 30 miles to 250 miles above the earth. Actually, the outer limit is many miles farther away.

The ionosphere differs from the other atmosphere in that it contains a much higher number of positive and negative ions. In the atoms of many substances, such as gases, one or more of the outer electrons, which revolve around the nucleus of the atom somewhat as the planets revolve around the sun, are detached from the atom, thus leaving the atom as a whole with a net positive charge. In this situation, the atom is said to be ionized. The negative ions (electrons) are produced by ultraviolet and particle radiations from the sun. The rotation of the earth on its axis, the annual course of the earth around the sun, and the development of sunspots all affect the number of ions present in the

ionosphere, and these in turn affect the quality and distance of radio transmission.

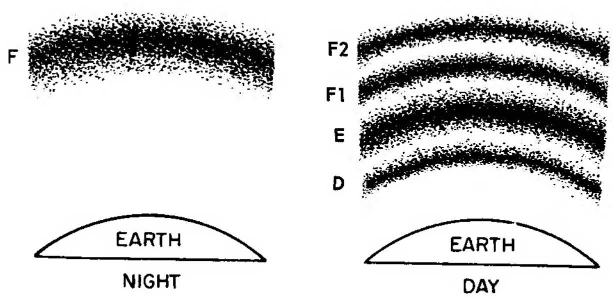
The ionosphere is changing constantly. Some of the ions are recombining to form neutral atoms, while other atoms are being split to form ions. The rate of formation and recombination of ions depends upon the amount of air present and the strength of the sun's radiations.

At altitudes above 250 miles, the particles of air are too sparse to permit large-scale ion formation. At altitudes less than 30 miles, too few ions exist to affect materially skywave communication.

Beyond the ionosphere lies the exosphere, which, without the aid of satellites, has no effect on communications.

Ionospheric Layers

Different densities of ionization at different heights make the ionosphere appear to have layers. Actually there is thought to be no sharp dividing line between layers, but for the purpose of discussion a sharp demarcation is indicated. In order of increasing heights and intensities, the layers of the ionosphere are identified as the D, E, F1, and F2 layers. The relative distribution of the layers is indicated in figure 6-8. As can be seen, all four layers are present only during the daytime, when the sun is directed toward that portion of the atmosphere. During the night, the F1 and F2 layers seem to merge into a single F layer, the D and E layers fading out or at least becoming noticeably weaker. This is only a general concept, however. The actual number of layers, their heights, and their relative intensities of ionization apparently vary constantly, even from hour to hour.



13.28

Figure 6-8. —Relative distribution of ionospheric layers.

The ionized atmosphere at an approximate altitude of between 30 and 50 miles is designated the D layer. Its ionization is low and has little effect on the propagation of radio waves except for the absorption of energy from the radio waves as they pass through it. The D layer is present only during the day. This reduces greatly the field intensities of transmissions that must pass through daylight zones.

At heights between 50 and about 100 miles lies the band of atmosphere containing the E layer. The ionization of the E layer follows the sun's altitude variations closely, reaching a maximum at about noon local time. During the middle of the day, however, ionization of the E layer may be sufficiently intense to refract frequencies up to 20 mc. Thus the E layer is of great importance to daylight transmissions for distances up to 1500 miles. Ionization fades to such a weak level during the night as to be practically useless as an aid to high-frequency communication.

The F layer extends approximately from the 100-mile level to the upper limits of the ionosphere. At night, only one F layer is present; but during the day, especially when the sun is high, this layer often separates into two parts, F1 and F2, as shown in figure 6-8. The F2 layer is the most highly ionized of all the layers, and is the most useful for long-range communication. The degree of ionization of this layer exhibits an appreciable day-to-day variation in comparison with that of the other layers. The intensity of ionization reaches a maximum in the afternoon and gradually decreases throughout the night. The rise of ion density is very rapid in the morning, and the low recombination rate permits the high ion intensity to persist.

Ionospheric Variations

Because the existence of the ionosphere depends on radiations from the sun, it is obvious that the movement of the earth about the sun, or changes in the sun's activity that might cause an increase or decrease in the amount of its radiation, will result in variations of the ionosphere. These variations include (1) those which are more or less regular in their nature and therefore can be predicted in advance, and (2) irregular variations resulting from abnormal behavior of the sun. The regular variations may be divided into four classes: daily, seasonal, 11-year, and 27-day variations.

DAILY.—Daily ionospheric variations were discussed in the description of the F layer. The increased ionization during the day is responsible for important changes in skywave transmission. For one thing, it causes the skywave to be returned to earth closer to the point of transmission. Another consideration is that the extra ionization increases the absorption of energy from the wave, resulting in greater wave attenuation.

To compensate for daily variations, it is suggested that higher frequencies be employed during the daytime than at night. The main reason for this is that the greater daytime ionization of the F2 layer refracts waves of higher frequency than the same layer does at night. Further, the higher the frequency employed, the less attenuation occurs as the r-f energy passes through the D region.

SEASONAL.—As the apparent position of the sun moves from one hemisphere to the other with changes in season, the maximum ionization in the D, E, and F1 layers shifts accordingly, each being greater during the summer. The F2 layer, however, does not follow this pattern in seasonal shift. In most localities, the F2 ionization is greatest in winter and least in summer, the reverse of what might be expected. The separation of the F1 and F2 layers is not so well defined in summer, because the height of the F2 layer is less during that season.

11-YEAR SUNSPOT CYCLE.—Sunspot activity varies according to an 11-year cycle. Sunspots affect the amount of ultraviolet radiation and hence affect the ionization of the atmosphere. During periods of high sunspot activity, ionization of the various layers is greater than usual, resulting in higher critical frequencies for the E, F1, and F2 layers, and higher absorption in the D region. This permits the use of higher frequencies for communication over long distances at times of greatest sunspot activity. The increased absorption in the D region, which has the greatest effect on the lower frequencies, requires that higher frequencies be used, but the overall effect is an improvement in propagation conditions during years of maximum sunspot activity.

27-DAY SUNSPOT CYCLE.—The 27-day sunspot variation is caused by the rotation of the sun on its axis. As the number of sunspots changes from day to day with rotation of the sun or the formation of new spots or the disappearance of old ones, absorption by the D region also changes. Similar changes observed in the E layer cover a wide geographic range. Fluctuations in the F2 layer are greater than for any other layer, but generally are not of a worldwide character.

IRREGULAR VARIATIONS.—A number of transient and unpredictable events bear on skywave propagation. Some of the more prevalent are: sporadic E ionizations, sudden ionospheric disturbances and storms, and scattered reflections.

Sporadic E ionizations are erratic patches of ionized cloud that appear in the area of E layer heights. These ionized clouds vary greatly in density. At times, they reflect so much of the radiated wave that reflections from the other layers of the ionosphere are blanked out completely. At other times, the sporadic E may be so thin that reflections from the upper layers can be received easily through it. The sporadic E layer may occur during the day or night; its occurrence is frequent, although more prevalent in the tropics than in the higher latitudes.

The most startling of all the irregularities of radio wave transmission is the sudden type of ionospheric disturbance causing a radio fadeout. This disturbance, caused by a solar eruption, comes without warning and may last for several hours. All stations on the sunlit side of the earth are affected. At the onset of the disturbance, receiving operators are inclined to believe that their radio sets suddenly have gone dead. The solar eruption causes a sudden increase in the ionization of the D region, frequently accompanied also by disturbances in the earth's magnetic field. The increased ionization of the D region usually causes total absorption of the skywave at all frequencies above 1000 kc.

An ionospheric storm may last from several hours to several days and usually extends over the entire earth. High-frequency skywave transmission is subject to severe fading, and wave propagation is erratic. Often it is necessary to lower the frequency to maintain communications during one of these storms.

Scattered reflections often occur from irregular layers in the ionosphere and may occur at all seasons, both day and night. A radio wave can reflect from either the top or bottom of one of these scattering ionospheric clouds, causing signal distortion and so-called flutter fading. In general, the fading is of short duration, and usually no compensation by the radio operator is required.

FADING AND FREQUENCY BLACKOUTS

Fading is a term used to denote variations in signal strength at the receiver. There are several causes; some are easily understood, others are more complicated. Frequency blackouts are related closely to some types of fading. In reality, a blackout is a complete fade, blotting out the entire transmission.

Fading

One cause of fading is the direct result of interference between single-hop and double-hop transmissions. If the two waves arrive in phase, the signal strength is increased; if the phases are opposed, they cancel each other and weaken the signal. This is called interference fading.

Interference fading also is severe in regions where the groundwave and skywave are in contact with each other. This is especially true if the two are approximately of equal strength. Fluctuations of the skywave with a steady groundwave can cause worse fading than the skywave transmission alone.

The variations in absorption and the path of the wave in the ionosphere are responsible for absorption fading. Occasionally, sudden ionospheric disturbances cause complete absorption of all skywave radiations.

Receivers located near the outer edge of the skip zone are subjected to skip fading as the skywave alternately strikes and skips over the area. This type of fading is so complete sometimes that signal strength falls to near zero level.

Additional variation in the field intensity affecting the receiving antenna occurs as a result of changes in the state of polarization of the downcoming wave relative to the orientation of the antenna. This variation is called polarization fading. The result is random and constantly changing values of the amplitude and orientation of the electric field with respect to the receiving antenna. The state of polarization of skywaves varies more rapidly the higher the frequency, which accounts in part for the rapid fading of higher frequencies.

Frequency Blackouts

Changing conditions in the ionosphere shortly before sunrise and after sunset may cause blackouts at certain frequencies. Higher frequencies may pass through the ionosphere, while the lower ones are absorbed by it. Ionospheric storms often cause erratic communications. Some frequencies are blacked out, although others are reinforced.

When frequency blackouts occur, radio operators must be alert to prevent complete loss of contact with other ships or stations. In severe storms, critical frequencies are much lower and absorption in the lower layers of the ionosphere is much higher.

MUF AND FREQUENCY TABLES

You know that for any fixed distance of transmission there is an upper limit of frequency that returns to earth at that distance. The existence of this upper-limit frequency depends on the ionization in the ionosphere reflecting only waves of frequencies less than a certain critical value; this value is referred to as the maximum usable frequency (MUF). The critical frequency is not constant. It varies from one location to another, with the time of day, the season of the year, and according to the sunspot cycle. Despite these variations in the critical frequency, usually it is desirable to transmit on a frequency as near the MUF as possible. Because there is a direct relationship between the MUF, the condition of the ionosphere, and time, it is possible to predict the MUF for any transmission path.

The National Bureau of Standards receives and analyzes ionospheric data from many stations throughout the world. This ionospheric information, in the form of MUF predictions, is made available to the Armed Forces and many other users.

To assist the Navy communicator, the DNC 14 series, entitled Recommended Frequency Bands and Frequency Guide, is published quarterly, 3 months in advance. This publication contains hourly predicted readings for the FOT (frequency for optimum traffic—approximately 85 percent of the MUF) and the lowest usable frequency (LUF) for communications on an area-by-area basis. Communications frequency predictions are available from 0 to 2400 miles. Directions for selection of working frequencies are contained in DNC 14.

To the Navy communicator an important part of the frequency spectrum lies in the medium- and high-frequency bands (2000 to 18,000 kc). These bands are used for long-distance naval communications from ship-to-ship and ship-to-shore. Standard transmitters found on most ships operate within this range of frequencies.

RADIOFREQUENCY PROPAGATION DETERMINATION AND PREDICTION SYSTEM

During periods of high solar activity, ionization of the ionosphere increases markedly. The range of MUFs for a particular long-range HF transmission path extends upward, occasionally reaching into the VHF band.

Low solar activity has the opposite effect. Ionospheric electron density decreases, and the ionosphere iwll not support the higher frequencies in the HF position of the r-f spectrum. As a result, congestion in the HF band becomes acute during periods of low solar activity because the usable portion of the HF spectrum is greatly reduced.

In addition to the adverse effects of low solar activity, communications are affected by solar-magnetic disturbances. These are caused by solar flares—nuclear explosions in the vicinity of the sun—and are cataloged according to their origin and effect on propagation. The more extreme disturbances are called "sudden ionospheric disturbances (SIDs)." Following a solar flare, radio circuits must await restoration until nature restores the equilibrium or successful alternate routing is accomplished through a time-consuming trial-and-error process.

Long-range frequency predictions are based in part on an ionospheric model in which the index of solar activity is on a statistical basis under assumed conditions of normal magnetic activity. Unfortunately, then, the DNC 14 series is deficient in at least one important respect: Predictions are predicated upon data based on undisturbed ionospheric conditions that exist only about 85 percent of the time. The predictions thus are suspect when conditions of ionospheric disturbances prevail. Even under so-called normal conditions, long-range frequency predictions provide only an average long-range guide to frequency selection.

From the preceding discussion, we can see that there is a vital need for an instrumental system to improve the reliability of HF communications by furnishing propagation data on an instantaneous basis. Ideally, such data would include the commencement, duration, and expected degree of circuit outages resulting from solar-magnetic disturbances. There should be an automatic correlation of factors affecting communication systems to permit the optimum utilization of frequencies in meeting operational requirements. To meet this demand, the Radio Frequency Propagation Determination and Prediction System has been established.

The underlying theme of the System is the development of a synchronized best frequency selection method to improve the overall reliability of naval communications. Present prediction methods are based on long-term propagation conditions, and the inability to determine short-term conditions is a major cause of circuit outages.

One result of the System was the introduction into the fleet of a facsimile propagation map. With the use of transmitted FAX broadcast contour maps, ships at sea are provided with up-to-date information on the best ship-to-shore frequencies during a specified period. A general 48-hour radio condition forecast is included as an integral part of the FAX map.

A project under development is the backscatter/oblique ionospheric sounding system. The backscatter principle provides for the return of a signal to the transmitting station over relatively the same path along which it was transmitted. The information obtained, displayed visually on electronic scopes, will give a presentation of the signal amplitude and area of illumination (estimated frequency coverage). The transmitting station thus will have real-time (instantaneous) knowledge regarding the adequacy of its transmission. Reception of the same transmission by the receiving station, in what is called the oblique mode, will provide a visual display yielding information concerning the best usable frequency for reception.

Ultimately, computer techniques will be employed to intercept and record backscatter/oblique sounding data, thereby establishing short-term propagation trends. Selected NAVCOMMSTAs and fleet units will be able to correlate prerecorded information with a control computer located at a frequency control center. Following a request from the operating forces for information expressed in terms of traffic load, bandwidth requirements, and time of desired operation, the control center will correlate the requirements with available information such as station equipment characteristics, propagation prediction and ionospheric-disturbance data, ship movement information, and available frequencies. The computer process will culminate in the automatic assignment of a portion of the spectrum to the operating unit in question.

SATELLITE COMMUNICATIONS

It should be apparent by now that one of the paramount problems facing the communicator is selecting the optimum operating frequency. Our usable portion of the r-f spectrum for long-range (HF) communications is confined to a frequency range of between 2 and 28 mc. To aggravate the problem, there are times when frequency blackouts occur and no usable frequencies are available.

One solution to the crowded HF spectrum difficulty lies in the field of satellite-relayed communications. Frequencies in the UHF band or above are considered (groundwave) line of sight frequencies because the nearly horizontal skywave passes through the ionosphere and the r-f energy is lost in space. If we substitute a satellite for the ionosphere or beyond the ionosphere to either reflect signals back to earth or amplify and retransmit the signals, we can utilize frequencies higher than those in the HF band. Longer ranges are available, depending on the height of the satellite, and we no longer depend on the ionosphere for long-range communications. More important, we are able to relieve the crowded area of the HF spectrum, thereby increasing greatly the amount of information that might be passed.

An interesting sidelight to the satellite relay of high-frequency transmissions is the proven feasibility of meteor burst communications. This technique utilizes the ionized trails of meteors as reflecting mediums for VHF transmissions. Meteor burst communications are difficult to jam, relatively secure from interception, and are not affected seriously by ionospheric disturbances.

In view of the known benefits obtainable by the use of frequencies above the HF spectrum, experiments also are being made utilizing lower frequencies. The U. S. Naval Research Laboratory's LOFTI (low-frequency transionospheric) satellite, for example, conformed the belief of some scientists that the ionosphere is not nearly as opaque at low frequencies as was generally assumed.

Although much of a radio wave is reflected by the ionosphere, LOFTI demonstrated that in the VLF area some of the r-f energy passes through the ionosphere into the exosphere with relatively little attenuation. The satellite's orbit ranged between an apogee of 600 miles and a perigee of 100 miles. The VLF signals (18 kc) to the bird were received both day and night at all heights. Further, the signals were of much greater density than anticipated. Even at a distance of some 10,000 miles from the transmitting station, remarkably strong signals are apparent in the telemetry records of the flight. Within LOFTI, received signals were amplified and retransmitted by telemetering equipment to ground stations on a frequency of 136 mc.

Communication satellites are of two types—passive and active.

A passive satellite is an object in orbit capable of reflecting a transmitted signal back to earth. It contains no energized electronic circuitry of its own. The Navy has developed the Communications Moon Relay (CMR) system using the passive reflection method for communications between Washington, D. C. and Pearl Harbor. The totality of the satellite need not be a solid surface; dispersed metallic particles may be utilized as reflectors. If these particles are of the proper length, they become resonant to a particular frequency, and reradiate any signals on that frequency. A disadvantage of the passive satellite is that effective communications using the satellite as a reflecting medium require large, sophisticated, high-gain antennas, and fairly high-powered transmitters.

An active satellite contains electronic receivers, power sources, amplifiers, and transmitters that receive an incoming transmission, amplify it, perhaps change its frequency (as in the LOFTI), and retransmit it to another ground station. Because the active satellite boosts the energy level of a relayed signal, it performs a function similar to a microwave relay tower on the ground. For this reason, ground transmitters need less power and smaller antennas as compared to the requirements of a passive satellite. This is an advantage to shipboard structure. Active satellites are the less reliable of the two types because they contain electronic circuitry and are, therefore, subject to equipment and circuit malfunctions.

Active satellites are further divided into two groups: delayed repeaters and real-time repeaters. Information received by a delayed repeater satellite is stored in a memory device, such as a tape recorder, and later is transmitted either on demand or automatically according to a planned sequence. The delayed repeater is useful at low altitudes when the satellite is not in the line of sight of the sending and receiving stations simultaneously. A real-time repeater, of course, repeats instantaneously with no time lag.

One of the most interesting methods of communications via active satellite is being experimented with in the Defense Communication Satellite Program, in which the Navy is a participant. This high-capacity global communication system calls for several satellites equally spaced around the world in 24-hour equatorial orbits. If the satellite is in an equatorial orbit and at sufficient altitude (19,300 miles from the earth's surface), its orbit will match the rotation of the earth and appear as a stationary satellite permanently fixed over a predetermined location. Ships and stations located anywhere on the earth from 70° N. to 70° S. should be able to view one of these satellites and conceivably could transmit at any time of the day to any place on the globe, within the foregoing latitude limits. Any number of methods of transmission will be available to this system, including digital data, SSB, and possible reconnaissance television. Because the frequency will be between 2000 and 8000 mc, the capacity of the system will be very high. Terminals for the eventual communication system will include fixed and mobile ground stations, aircraft, ships, and submarines.